Discovery of Very-High-Energy γ-Rays from the Galactic Centre Ridge

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The origin of Galactic cosmic rays (with energies up to 10^{15} eV) remains unclear, though it is widely believed that they originate in the shock waves of expanding supernova remnants [1][2]. Currently the best way to investigate their acceleration and propagation is by observing the γ-rays produced when cosmic rays interact with interstellar gas [3]. Here we report observations of an extended region of very high energy (VHE, >100 GeV) γ-ray emission correlated spatially with a complex of giant molecular clouds in the central 200 pc of the Milky Way. The hardness of the γ-ray spectrum and the conditions in those molecular clouds indicate that the cosmic rays giving rise to the γ-rays are likely to be protons and nuclei rather than electrons. The energy associated with the cosmic rays could have come from a single supernova explosion around 10^4 years ago.

The observations described here were carried out with the High Energy Stereoscopic System (H.E.S.S.), a system of four imaging atmospheric-Cherenkov telescopes [4]. The instrument operates in the Teraelectronvolt energy range (TeV), beyond the regime accessible to satellite-based detectors (MeV up to $\sim$10 GeV). At satellite energies, the technique of probing the distribution of cosmic rays (CRs) using γ-ray emission has been demonstrated in the large-scale mapping of the Galactic plane by EGRET [5]. The γ-ray flux was found to approximately trace the density of interstellar gas, illustrating that the flux of CRs is roughly constant throughout the Galaxy. However, given its modest angular resolution ($\sim 1^\circ$), EGRET could only resolve the few nearest molecular clouds. The order of magnitude better angular resolution of H.E.S.S. opens up this possibility of resolving individual clouds out to the distance of the Galactic Centre (GC). Moreover, in the energy range accessible to EGRET, the picture is complicated by the contribution of cosmic electrons [1] to the diffuse γ-ray flux via inverse Compton (IC) scattering and Bremsstrahlung. In the energy range of H.E.S.S. the dominant component of the truely diffuse γ-ray emission is very likely the decay of neutral pions produced in the interactions of CRs with ambient material. Taken together, the wide field of view ($\sim$5°) and the improved angular resolution (better than 0.1°) of H.E.S.S. have made possible the mapping of extended γ-ray emission.

Early H.E.S.S. observations of the GC region led to the detection of a point-like source of VHE γ-rays at the gravitational centre of the Galaxy (HESS J1745$-$290) [6], compatible with the positions of the supermassive black hole Sagittarius A*, the supernova remnant (SNR) Sgr A East, and a GC source reported by other groups [7, 8]. A more sensitive exposure of the region in 2004 revealed a second source: the supernova remnant/pulsar wind nebula G 0.9+0.1 [9]. These two sources are clearly visible in the upper panel of Fig. 1. For previous VHE instruments such sources were close to the limit of detectability. With the greater sensitivity of the H.E.S.S. instrument it is possible to subtract these two sources and search for much fainter emission. Subtracting the best fit model for point-like emission at the position of these excesses yields the map shown in Fig. 1 (bottom). Two significant features are apparent after subtraction: extended emission spatially coincident with the unidentified EGRET source 3EG J1744-3011 (discussed elsewhere [10]) and emission extending along the Galactic plane for roughly 2°. The latter emission is not only very clearly extended in longitude l, but also significantly extended in latitude b (beyond the angular resolution of H.E.S.S.) with a characteristic root mean square (rms) width of 0.2°, as can be seen in the Galactic latitude slices shown in Fig. 2. The reconstructed γ-ray spectrum for the region $-0.8^\circ < l < 0.8^\circ$, $|b| < 0.3^\circ$ (with point-source emission subtracted) is well described by a power law with photon index $\Gamma = 2.29 \pm 0.07_{stat} \pm 0.20_{sys}$ (Fig. 3).

Given the plausible assumption that the γ-ray emission takes place near the centre of the Galaxy, at a distance of about 8.5 kpc, the observed rms extension in latitude of 0.2° corresponds to a scale of $\approx$ 30 pc. This value is similar to that of interstellar material in giant molecular clouds in this region, as traced by their CO emission and in particular by their CS emission [11]. CS line emission does not suffer from the problem of 'standard' CO lines [12], that clouds are optically thick for these lines and hence the total mass of clouds may be underestimated. The CS data suggest that the central region of the Galaxy, $|l| < 1.5^\circ$ and $|b| < 0.25^\circ$, contains about $3-8\times10^7$ solar masses of interstellar gas, structured in a number of overlapping clouds, which provide an efficient target for the nucleonic CRs permeating these clouds. The region over which the γ-ray spectrum is integrated contains 55% of the CS emission, corresponding to a mass of $1.7-4.4\times10^7$ solar masses. At least for $|l| < 1^\circ$, we find a close match between the distribution of the VHE γ-ray emission and the density of dense interstellar gas as traced by CS emission (Fig. 1 (bottom) and Fig. 2).

The close correlation between γ-ray emission and available target material in the central 200 pc of our galaxy is a strong indication for an origin of this emission in the interactions of CRs. Following this interpretation, the similarity in the distributions of CS line and VHE γ-ray emission implies a rather uniform CR density in the region. Since in the case of a power-law energy distribution the spectral index of the γ-rays closely traces the spectral index of the CRs themselves (corrections due to scaling violations in the CR interactions are small, $\Delta\Gamma < 0.1$), the measured γ-ray spectrum implies a CR spectrum near the GC with a spectral index close to 2.3, significantly harder than in the solar neighbourhood (where an index of 2.75 is measured). Given the probable

proximity of particle accelerators, propagation effects are likely to be less pronounced than in the Galaxy as a whole, providing a natural explanation for the harder spectrum which is closer to the intrinsic CR-source spectra. The main uncertainty in estimating the flux of CRs in the GC is the uncertainty in the amount of target material. Following [3] and using the mass estimate of Tsuboi [11] we can estimate the expected γ-ray flux from the region, assuming for the moment that the GC cosmic-ray flux and spectrum are identical to those measured in the solar neighbourhood. Fig. 3 shows the expected γ-ray flux as a grey band, together with the observed spectrum. Whilst below 500 GeV there is reasonable agreement with this simple prediction, there is a clear excess of high energy γ-rays over expectations. The γ-ray flux above 1 TeV is a factor $3-9$ higher than the expected flux. The implication is that the number density of CRs with multi-TeV energies exceeds the local density by the same factor. The size of the enhancement increases rapidly at energies above 1 TeV.

The observation of correlation between target material and TeV γ-ray emission is unique and provides a compelling case for an origin of the emission in the interactions of CR nuclei. In addition, the key experimental facts of a harder than expected spectrum, and a higher than expected TeV flux, imply that there is an additional component to the GC cosmic-ray population above the CR 'sea' which fills the Galaxy. This is the first time that such direct evidence for recently accelerated (hadronic) CRs in any part of our galaxy has been found. The energy required to accelerate this additional component is estimated to be 10^{49} erg in the energy range 4-40 TeV or $\sim 10^{50}$ erg in total if the measured spectrum extends from $10^{9}-10^{15}$ eV. Given a typical supernova explosion energy of 10^{51} erg, the observed CR excess could have been produced in a single SNR, assuming a 10% efficiency for CR acceleration. Following such a scenario, any epoch of CR production must have occurred in the recent enough past that the CRs accelerated have not yet diffused out of the GC region. Representing the diffusion of protons with energies of several TeV in the form $D = \eta 10^{30}$ cm^{2}s^{-1}, where 10^{30} cm^{2}s^{-1} is the approximate value of the diffusion coefficient in the Galactic Disk at TeV energies, we estimate the diffusion time-scale to be $t = R^2/2D \approx 3000(\theta\,/\,1^\circ)^2/\eta$ years, where θ is the angular distance from the GC. Due to the larger magnetic field and higher turbulence in the central region compared to more conventional regions of the Galactic disk, the normalisation parameter η is likely ≤ 1 and a source or sources of age $\sim$10 kyr could fill the region $|l| < 1^\circ$ with CRs. Indeed, the observation of a deficit in VHE emission at $l = 1.3^\circ$ relative to the available target material (see Fig. 2) suggests that CRs, which were recently accelerated in a source or sources in the GC region, have not yet diffused out beyond $|l| = 1^\circ$.

The observed morphology and spectrum of the γ-ray emission provide evidence that one or more cosmic-ray accelerators have been active in the GC in the last 10,000 years. The fact that the diffuse emission exhibits a photon index Γ which is the same - within errors - as that of the central source HESS J1745$-$290 suggests that this object could be the source in question. Within the 1 arcminute error box of HESS J1745$-$290 are two compelling candidates for such a CR accelerator. The first is the SNR Sgr A East [13] with its estimated age around 10 kyr [14] (younger ages have been quoted for Sgr A East [15] reflecting the significant uncertainty in this estimate). The second is the supermassive black hole Sgr A* [16, 17] which may have been more active in the past.

A distinct alternative possibility is that a population of *electron* accelerators produces the observed γ-ray emission via IC scattering. Extended objects with photon indices close to the value 2.3 observed in the GC are observed elsewhere in the Galactic plane [10]. The parent population of objects such as pulsar wind nebulae (i.e. massive stars) would likely follow approximately the distribution of molecular gas. However, in the intense photon fields and high magnetic fields within and close to the GC molecular clouds [18, 19], TeV electrons would lose their energy rapidly: $t_{\rm rad} \approx 120\,(B/100\,\mu{\rm G})^{-2}\,(E_e/10\,{\rm TeV})^{-1}$ years. We would therefore expect to see rather compact sources (point-like for H.E.S.S.) which would also be bright in the X-ray regime (as is for example G 0.9+0.1). The existence of ~ 10 such unknown sources in this small region again seems unlikely. Any substantially extended IC source would most likely be a foreground source along the line-of-sight towards the GC region, making any correlation with GC molecular clouds entirely coincidental.

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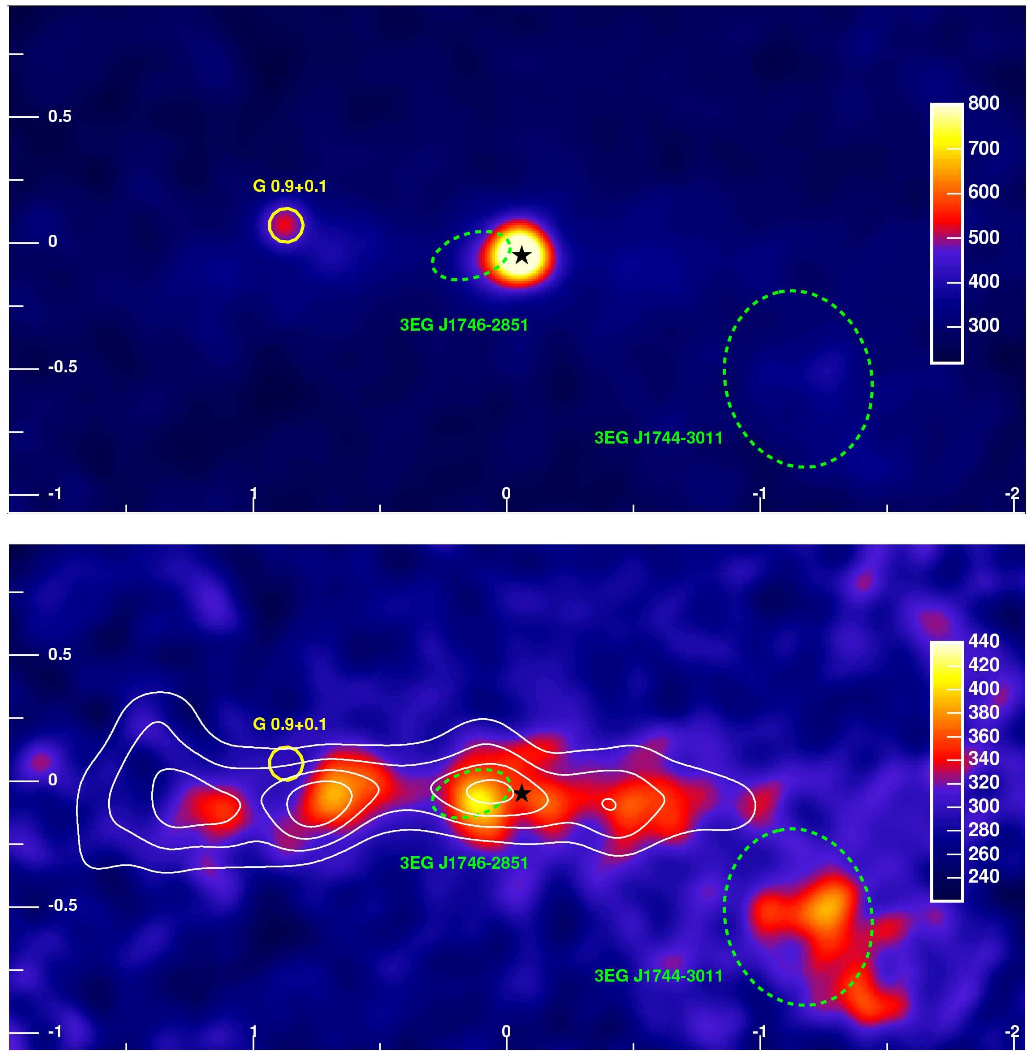

Figure 1: VHE γ-ray images of the GC region. Top: γ-ray count map, bottom: the same map after subtraction of the two dominant point sources, showing an extended band of gamma-ray emission. White contour lines indicate the density of molecular gas, traced by its CS emission. The position and size of the composite SNR G 0.9+0.1 is shown with a yellow circle. The position of Sgr A* is marked with a black star. The 95% confidence region for the positions of the two unidentified EGRET sources in the region are shown as dashed green ellipses [20]. These smoothed and acceptance corrected images are derived from 55 hours of data consisting of dedicated observations of Sgr A*, G 0.9+0.1 and a part of the data of the H.E.S.S. Galactic plane survey [21]. The excess observed along the Galactic plane consists of $\approx$3500 γ-ray photons and has a statistical significance of 14.6 standard deviations. The absence of any residual emission at the position of the point-like γ-ray source G 0.9+0.1 demonstrates the validity of the subtraction technique. The energy threshold of the maps is 380 GeV due to the tight γ-ray selection cuts applied here to improve signal/noise and angular resolution. We note that the ability of H.E.S.S. to map extended γ-ray emission has been demonstrated for the shell-type SNRs RX J1713.7 $-$3946 [22] and RX J0852.0$-$4622 [23]. The white contours are evenly spaced and show velocity integrated CS line emission from Tsuboi et al. [11], and have been smoothed to match the angular resolution of H.E.S.S..

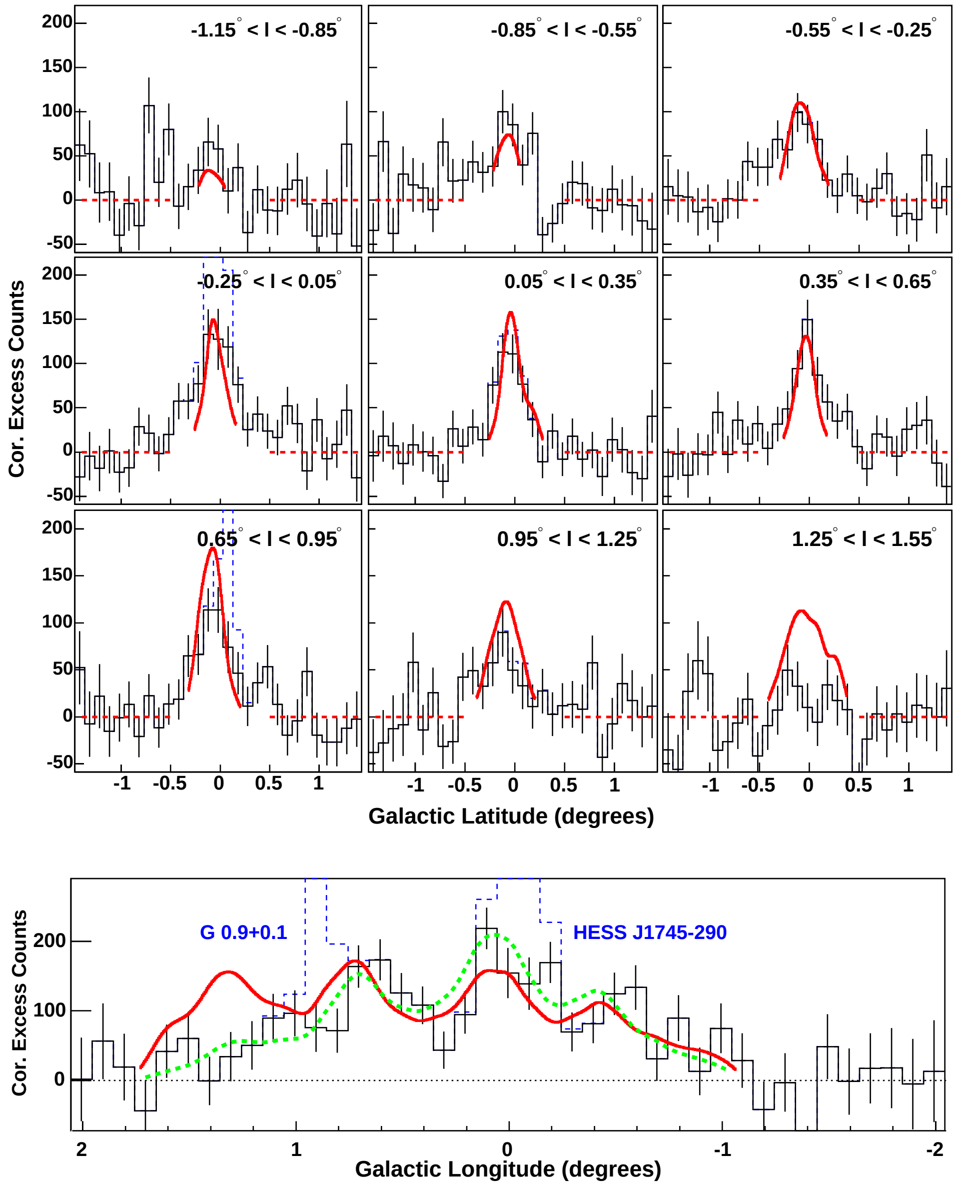

Figure 2: Distribution of γ-ray emission in Galactic latitude (for individual slices in longitude, top) and in Galactic longitude (bottom). The red curves show the density of molecular gas, traced by CS emission. The upper curves show acceptance corrected (and cosmic-ray background subtracted) γ-ray counts for $0.3°$ wide bands in longitude. The point-source subtracted counts are shown in black. The dashed blue histogram shows the unsubtracted values (the y-scale is truncated). The red curves correspond to the smoothed CS map of Fig. 1 and are drawn only in the regions where CS measurements are available. The dashed red lines show nominal zero CS density in regions away from the Galactic plane. The lower plot shows γ-ray counts versus l for $-0.2° < b < 0.2°$. The CS line flux may be underestimated close to $l = -1°$ due to a narrower coverage in b at this longitude. The dashed line shows the γ-ray flux expected if the CR density distribution can be described by a Gaussian centred at $l = 0°$ and with rms $0.8°$, as expected in a simple model for diffusion away from a central source of age $\sim 10^4$ years. In all plots the background level is estimated using events from the regions $0.8° < |b| < 1.5°$. Error bars show ± 1 standard deviation.

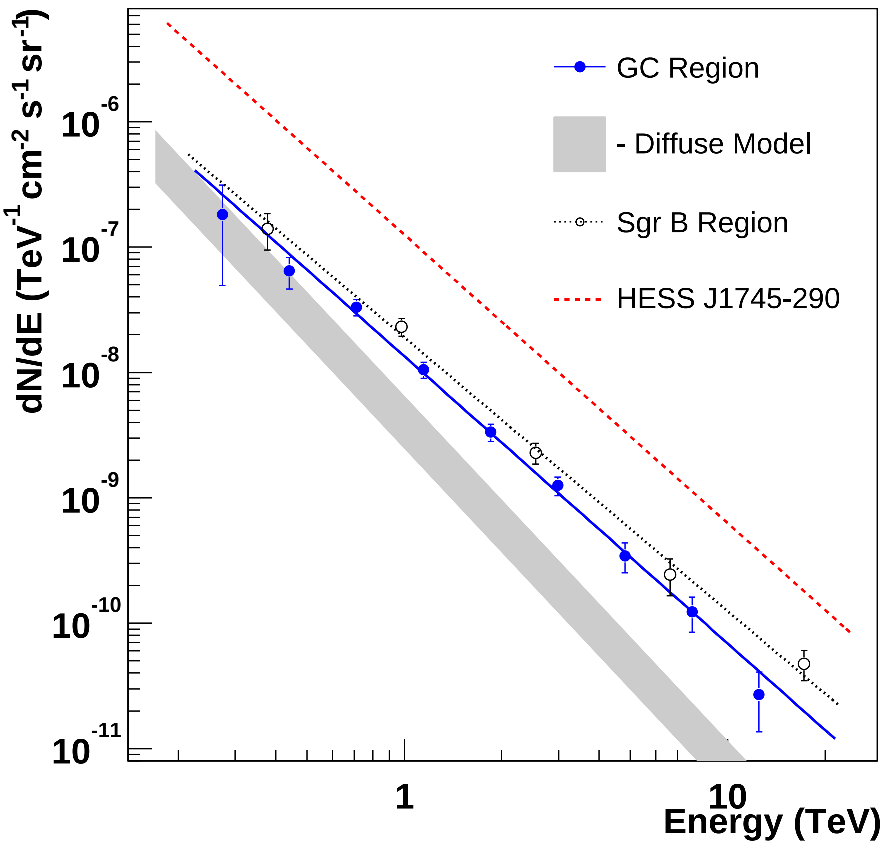

Figure 3: γ-ray flux per unit solid angle in the GC region (data points), in comparison with the expected flux assuming a cosmic-ray spectrum as measured in the solar neighbourhood (shaded band). The spectrum of the region $-0.8^\circ < l < 0.8^\circ$, $|b| < 0.3^\circ$ is shown using full circles. These data can be described by a power law: $dN/dE = k(E/\mathrm{TeV})^{-\Gamma}$, with $k = (1.73 \pm 0.13_{stat} \pm 0.35_{sys}) \times 10^{-8}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1} and a photon index $\Gamma = 2.29 \pm 0.07_{stat} \pm 0.20_{sys}$. The shaded box shows the range of expected π^0-decay fluxes from this region assuming a CR spectrum identical to that found in the solar neighbourhood and a total mass of $1.7 - 4.4 \times 10^7$ solar masses in the region $-0.8^\circ < l < 0.8^\circ$, $|b| < 0.3^\circ$, estimated from CS measurements. Above 1 TeV an enhancement by a factor $3 - 9$ relative to this prediction is observed. Using independent mass estimates derived from sub-millimeter measurements [24], $5.3 \pm 1.0 \times 10^7$ solar masses, and from $C^{18}O$ measurements [25], $3^{+2}_{-1} \times 10^7$ solar masses, results in enhancement factors of $4-6$ and $5-13$, respectively. The strongest emission away from the bright central source HESS J1745$-$290 occurs close to the Sagittarius B complex of giant molecular clouds [26]. In a box covering this region ($0.3^\circ < l < 0.8^\circ$, $-0.3^\circ < b < 0.2^\circ$), integrated CS emission suggests a molecular target mass of $6 - 15 \times 10^6$ solar masses. The energy spectrum of this region is shown using open circles. The measured γ-ray flux (> 1 TeV) implies a high-energy cosmic-ray density which is $4 - 10$ times higher than the local value. Standard γ-ray selection cuts are applied here, yielding a spectral analysis threshold of 170 GeV. The spectrum of the central source HESS J1745-290 is shown for comparison (using an integration radius of 0.14°). All error bars show ± 1 standard deviation.